

Impact of Weather on Aircraft Fuel Savings and
Operating Efficiency -- Results of a NASA Study

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Abstract

NASA conducted a 24 month study to determine the potential impact of more timely and accurate weather data on aircraft fuel savings and operating efficiency. The study involved the participation of several airlines and air traffic control centers, and utilized data from thousands of actual as well as computer developed flights.

The results showed that:

1. If the present operational forecast could be made available more often, then the average fuel savings would be about 2.5 percent eastbound and 1.2 percent westbound.
2. If the detail inherent in the observations could be retained so that the forecast reflected improvements in both timeliness and accuracy, then an additional 2.0 percent increase in fuel savings is possible.
3. On average the operational forecast always underestimated the wind speed by 13 knots and that this could result in an excess or shortfall of planned fuel by as much as 3.6 percent depending upon direction of flight.
4. One of the most important components of the aviation digital data is the automated pilot report; it is the key to more accurate flight

planning, additional fuel savings and improvements in operating efficiency.

5. Airlines which use a flight plan that does not provide for interpolation of weather data (and some 30 carriers use no interpolation) have a higher frequency of (about 3 times as many) flight segment errors* per flight plan as does a carrier which uses a simple bilinear interpolation technique.
6. The absolute magnitude of the flight plan wind speed, wind angle and air temperature errors (13.8 kts., 28.2 degrees and 2.9°C respectively) is independent of the interpolation (or lack of interpolation) technique used; inferring that it is the resolution of the aviation digital forecast, rather than the interpolation method that presently limits the accuracy of the flight plan.
7. Airlines whose selection of a track on North Atlantic routes is based on minimum time rather than minimum fuel, are on the wrong track 45 to 50 percent of the time.

*A flight segment error is defined as occurring when any one or more of the following criteria have been met:

wind speed greater than 20 knots
wind angle greater than 30 degrees
outside air temperature greater than 5°C
between flight plan forecasted and observed data.

8. A number of assumptions used by the airlines in developing their flight plans and minimum time/minimum fuel track models have been shown to be questionable and are in need of re-evaluation.
9. Of the 33 days which were arbitrarily selected over a 4 month period for flight plan reruns and a detailed evaluation, fifteen of the 33 days studied were shown to have significant forecast errors.
10. The present forecast/flight planning system is inadequate to meet the needs of the aviation industry in a high fuel cost environment.

I. Introduction

The impact of weather on aircraft operating efficiency and fuel savings has been discussed with increasing frequency over the past several years, because of the need to reduce operating costs. The purpose of the NASA study was to determine if improvements are possible and to quantify the results in terms that are meaningful to the aviation community. A detailed 24-month study was undertaken using the airline flight plan as a sensitive indicator of fuel savings, to evaluate the impact of more timely and accurate wind and temperature data, at cruise altitudes, on aircraft operating efficiency. The approach, first taken, was to remove the limiting elements of

1. old and less accurate weather data
2. air traffic control restrictions

in order to determine what the level of fuel savings could be under more ideal circumstances. Flight plans developed using an operational forecast* were compared with those developed using a verifying analysis**, valid at the time of the forecast¹. The computer developed

*Wherever the term operational forecast is used, this refers specifically to the 7 level primitive equation model used by the U.S. National Weather Service.

**Wherever the term verifying analysis is used, this refers to the Flattery analysis model used by the U.S. National Weather Service.

verifying analysis was supposed to represent "actual weather" but it used the same analysis model (Flattery analysis) also used in developing the operational forecast. So if, as it turned to be the case, the Flattery analysis was too coarse and tended to smooth out the input data detail,² then the flight plan comparisons made between flights on the same routes might only show a small difference; and that turned out to be the case. Further comparative analysis of isotach difference fields revealed that this approach was indeed distorting the results. Flight plan comparisons were then made between non-optimal routes (using the operational forecast) and minimum time track (MTT) routes (using the verifying analysis) which is the most significant comparison because of its direct correlations with present aircraft flight operations. These results showed a potential fuel savings on the North Atlantic of 2.5 percent eastbound and 1.2 percent westbound, under almost ideal conditions. Because the earlier data indicated that the verifying analysis (actual weather) could be limiting the results, a need arose to go beyond the use of the verifying analysis to a more accurate data set. It also became clear after looking at a number of airline flight plans, that the flight plan itself could be introducing additional restrictive factors and needed to be evaluated. The

list of limiting elements was now broadened to include the following:

1. verifying (Flattery) analysis model
2. airline flight plan model
3. airline minimum time/minimum fuel track models

In order to quantify the impact of these limiting factors, the study was enlarged in the following way:

(1) a series of seventy-five manual verifying analyses was developed for the North Atlantic which retained the detail implicit in the observations. These manual analyses were used to develop comparison MTT's, with those developed operationally by Gander Air Traffic Control (ATC); and (2) operational forecast fields (instead of flight plans) were also compared with actual data rather than computer developed verifying analyses in order to determine if it was the flight plan or the forecast which was providing the error.³

What follows is a summary of the main results⁴ developed by a contractor PRC Speas Incorporated, of Lake Success, New York and at NASA's Lewis Research Center. North Atlantic manual analyses and MTT's were developed by Mr. E.B. Buxton, a consulting meteorologist. Additional data analyses were also provided by Mr. J. Irving of the Civil Aviation Authority.

II. Results of Study

2.1 North Atlantic Flight Operations

Flight plan comparisons were made using an operational forecast vs. a verifying analysis, on the same non-optimal routes. The average fuel savings was 0.6 percent eastbound and -0.2 percent westbound. When, in addition to using the verifying analysis, operational constraints imposed by the North Atlantic Track (NAT) system were removed and a MTT at optimal levels was introduced, the average fuel savings per flight was 2.5 percent eastbound and 1.2 percent westbound. The above results were limited by the following factors:

1. verifying (Flattery) analysis model
2. airline MTT model
3. comparison data developed for August through November

In order to reduce or eliminate these limitations, a verifying manual analysis* and MTT's were developed for the North Atlantic. Seventy-five cases were run covering a period of from January to November. MTT's were developed using a manual analysis and compared to operational MTT's computer developed by Gander Air Traffic Control using an operational forecast.

*Note: A verifying manual analysis does not refer to the Flattery model.

These results showed a 3.9 percent time savings eastbound and a 0.8 percent savings westbound (note; it is inferred that time savings is to a first approximation equivalent to fuel savings; at cruise conditions this assumption is reasonable). Figures 1 and 2 show a representative sample of the Gander comparisons over a ten month period east and westbound. It can be seen that most of the MTT's developed on the verifying manual analysis show a time savings over the MTT's developed on an operational forecast (MTT's developed for FL340). Figure 3 shows that in many instances the time differences were accompanied by a significant physical displacement of the MTT. Figure 4 and Figure 5 summarizes all of the above results and shows the range of improvements which may be possible on the North Atlantic east- and westbound.

2.1.1 The North Atlantic Track System

For a period of 30 days using the operational forecast, computer generated flight plans were run for each track and altitude in an east/west mode between a number of city pairs to develop cross-sectional data (see Figure 6 for typical case) to determine if minimum fuel tracks (MFT) and MTT's were in close agreement.⁵ These results showed the following:

1. airlines whose track selection is based on an MTT rather than an MFT, and,...

MTT_A (based on manual verifying analysis) vs. Gander MTT_F (based on operational forecast)

(time in minutes)

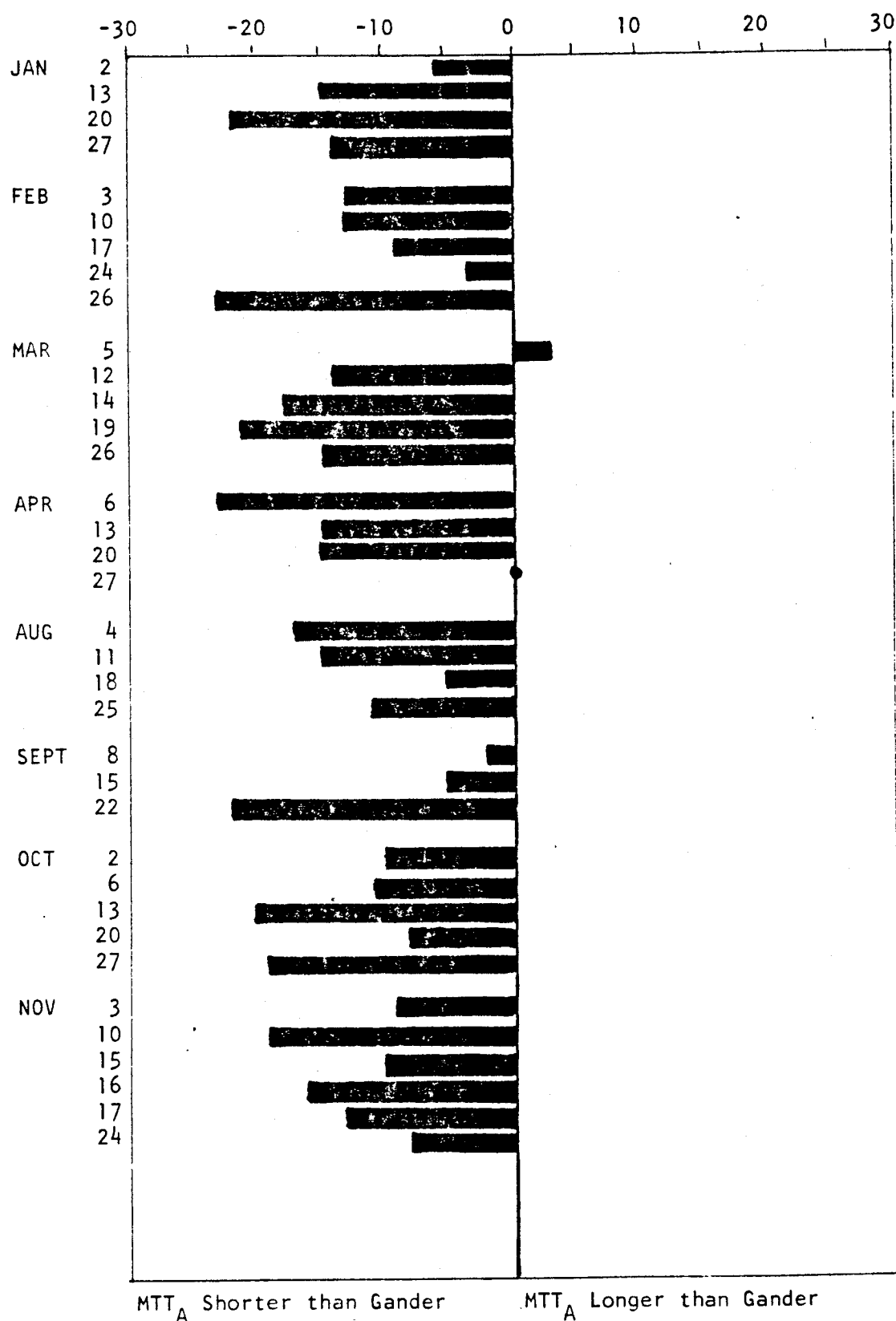


Figure 1. Shows Minimum Time Track Comparison Data

where MTT_A is minimum time track based on a manual verifying analysis
and MTT_F is minimum time track based on an operational forecast

NORTH ATLANTIC WEST-BOUND FLIGHTS

MTT_A (manual analysis) vs. Gander MTT_F (forecast)

(time in minutes)

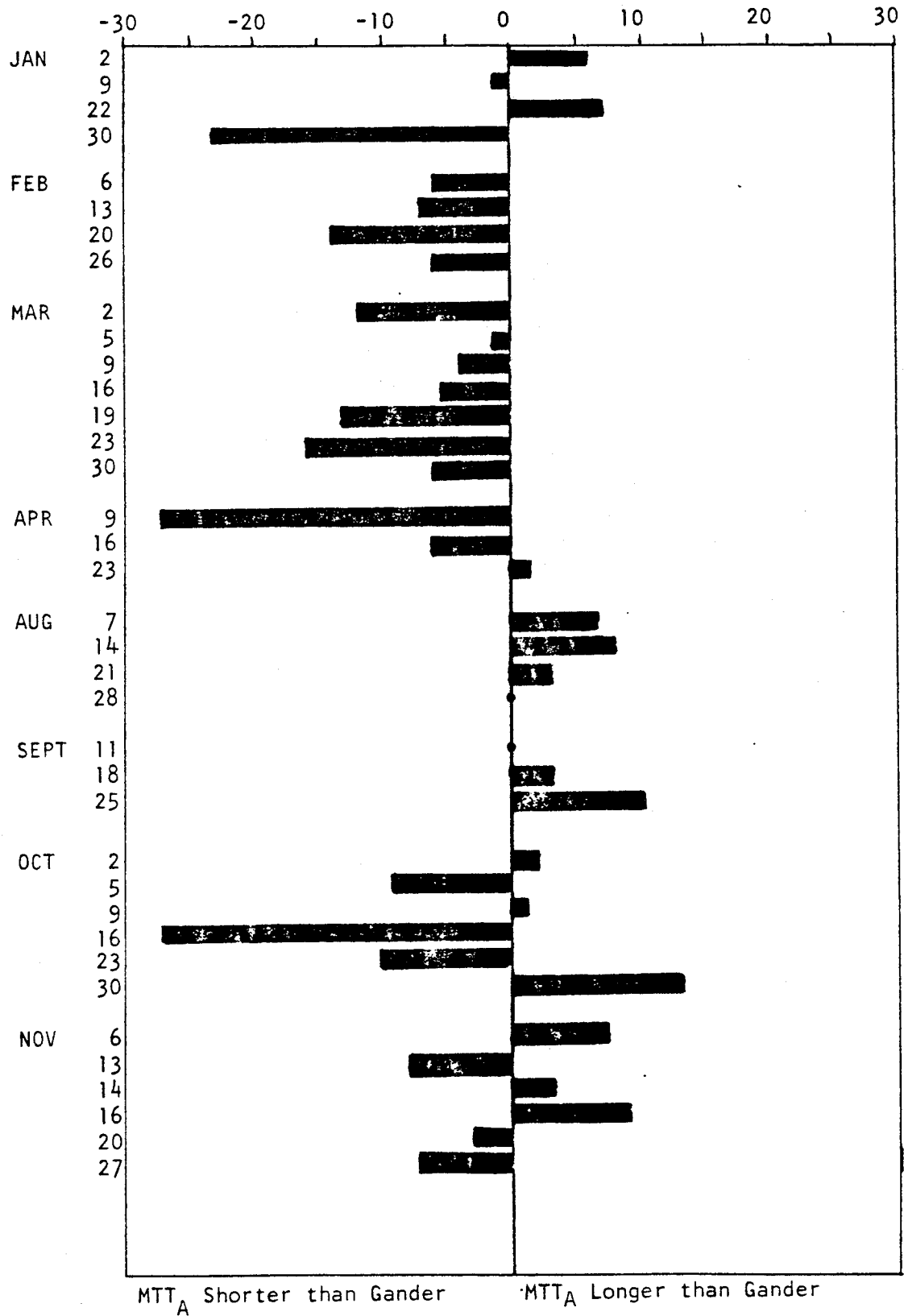


Figure 2. Shows Minimum Time Track Comparison Data

where MTT_A is minimum time track based on a manual verifying analysis
and MTT_F is a minimum time track based on an operational forecast

Figure 3. Shows difference between MT's (New York and London) calculated on a manual verifying analysis (BUX W/AIDS), the Gander MT using Suitland forecast and the Prestwick MT using the Bracknell forecast for Aug. 7, 11, 14 and 18.

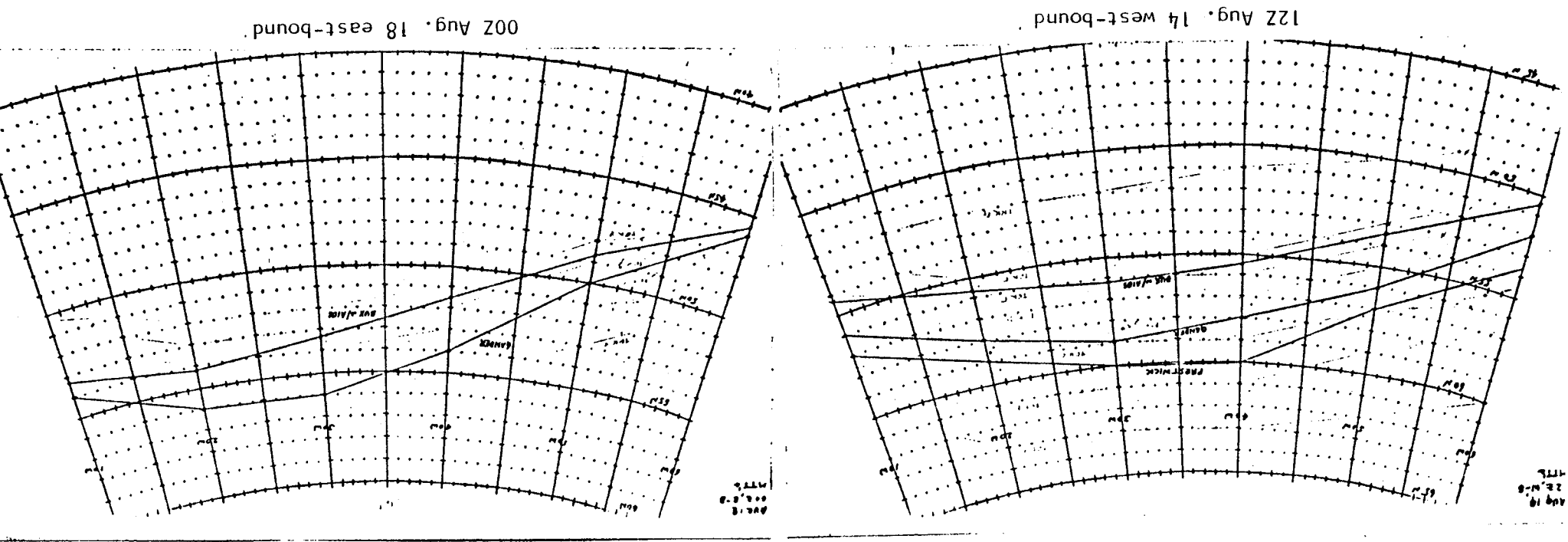
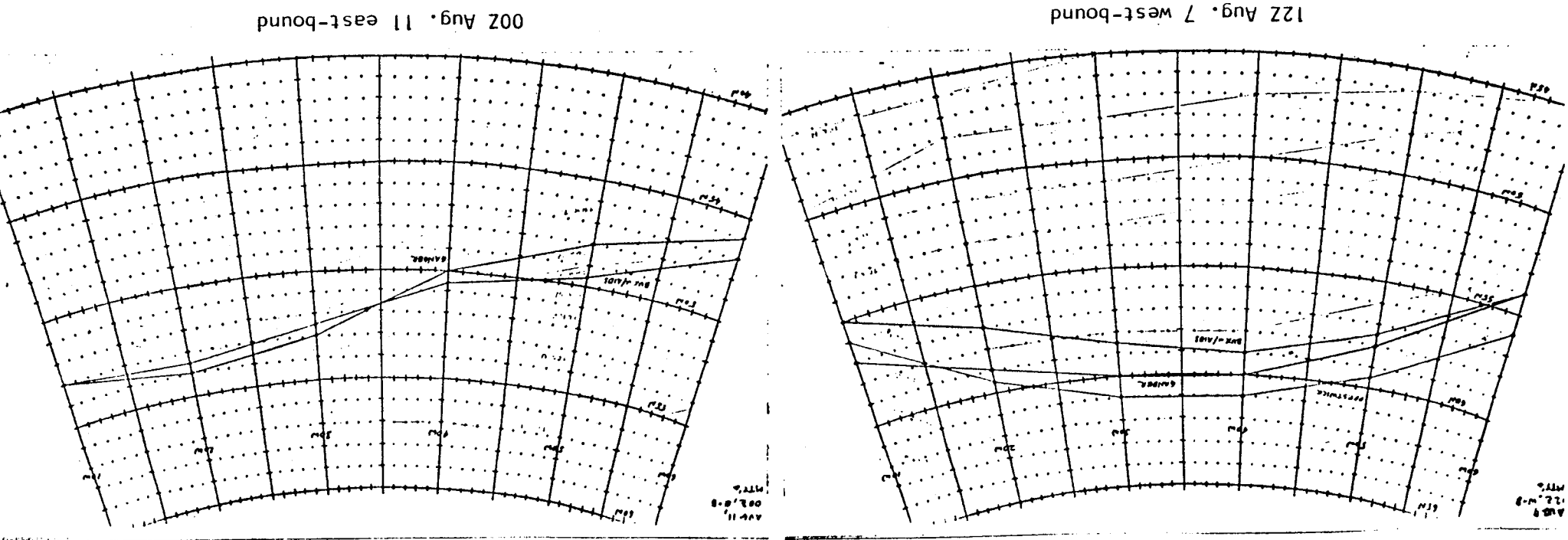


Figure 4. Range of Potential Improvements in Operating Efficiency
North Atlantic - Eastbound

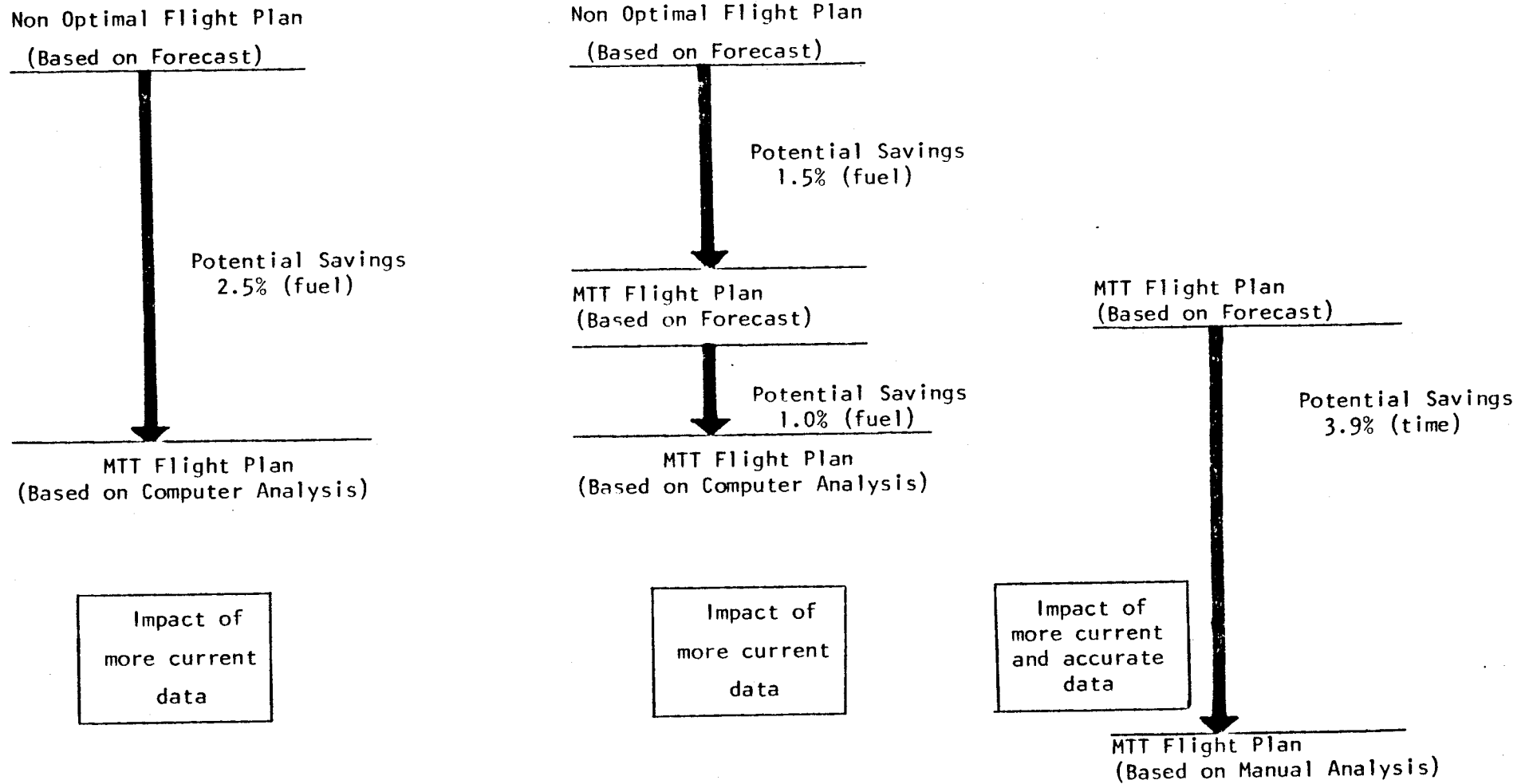


Figure 5. Range of Potential Improvements in Operating Efficiency

North Atlantic - Westbound

Non Optimal Flight Plan

(Based on Forecast)

Potential Savings
1.2% (fuel)

MTT Flight Plan

(Based on Computer Analysis)

Impact of
more timely
met data

Non Optimal Flight Plan

(Based on Forecast)

Potential Savings
1.6% (fuel)

MTT Flight Plan
Based on Forecast

Potential Savings
-0.4% (fuel)

MTT Flight Plan

(Based on Computer Analysis)

Impact of
more timely
met data

MTT Flight Plan
(Based on Forecast)

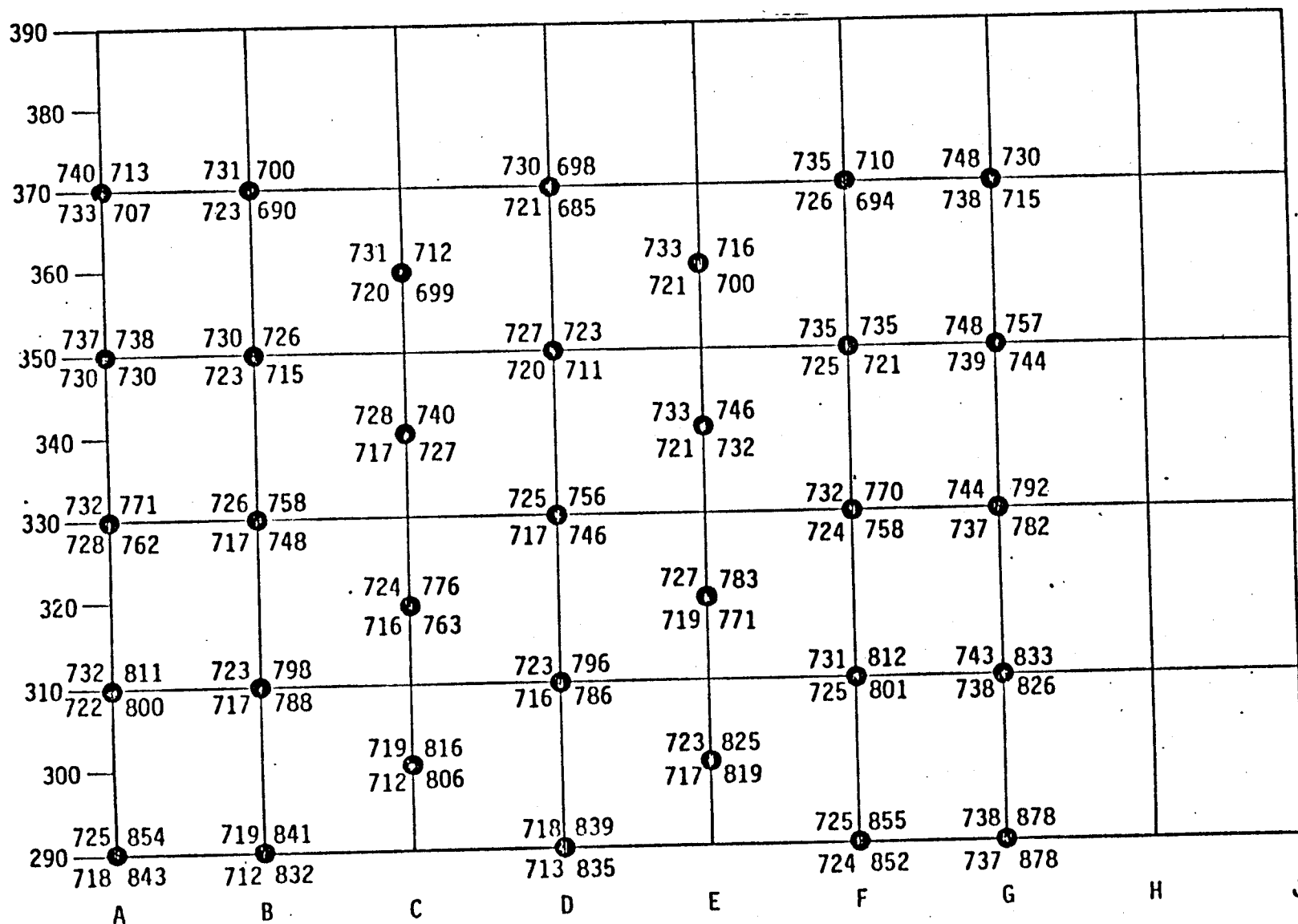
Potential Savings
0.8% (time)

MTT Flight Plan

(Based on Manual Analysis)

Impact of
more timely
more accurate
met data

Figure 6. Comparison of Time and Burn on North Atlantic Organized Tracks on Operational Forecast and Verifying Analyses (Day Tracks)



Source: Flight plans computed on BLUE flight planning system

Key:

TIME (Hrs & Min)	BURN (100 Kg)
Forecast	Forecast
Actual	Actual

2. airlines that select an MTT at a constant level before optimizing the flight level, do not select the optimum fuel track and altitude 45 to 50 percent of the time.

JFK-AMS and AMS-JFK track comparisons based on the operational forecast are shown in Table I and on the verifying analysis is shown in Table II. The data was developed for 30 days (one eastbound and one westbound case per day).

Table I

JFK-AMS/AMS-JFK MFT/MTT Comparisons Based on an Operational Forecast

MFT	0 tracks over from MTT	36 cases
MFT	1 tracks over from MTT	20 cases
MFT	2 tracks over from MTT	4 cases

Table II

JFK-AMS/AMS-JFK MFT/MTT Comparisons Based on a Verifying Analysis

MFT	0 tracks over from MTT	27 cases
MFT	1 tracks over from MTT	28 cases
MFT	2 tracks over from MTT	5 cases

The North Atlantic MTT selected by one airline at FL330 eastbound and FL350 westbound was also compared to

the MFT which was at one of the higher levels available in the system. Minimum time tracks developed from the forecast were compared to minimum fuel tracks on the verifying analysis, and the results are shown in Table III.

Table III

JFK-AMS/AMS-JFK MFT/MTT Comparisons
MFT Based on a Verifying Analysis vs. an MTT Based on a Forecast

MFT	0 tracks over from MTT	32 cases
MFT	1 tracks over from MTT	20 cases
MFT	2 tracks over from MTT	3 cases
MFT	3 tracks over from MTT	4 cases
MFT	4 tracks over from MTT	1 case

Comparisons were also made between a MFT developed on a forecast and one developed on an analysis; the results are shown in Table IV.

Table IV

JFK-AMS/AMS-JFK MFT/MFT Comparison Based on
Operational Forecast vs. a Verifying Analysis

MFT _A *	0 tracks over from MFT _F **	41 cases
MFT _A	1 tracks over from MFT _F	6 cases
MFT _A	2-6 tracks over from MFT _F	13 cases

2.2 Mid-Atlantic Flight Operations

At the time this study was proposed, it was the practice of at least one airline, and possibly more, to operate on a single fixed route between the Caribbean/Northern South America and Europe. This was due in part to ATC considerations and the belief of limited gains from track optimization in this area. This concept was tested by placing eight additional tracks, around the fixed routes and computer flying each track and altitude for a period of 30 days. Figure 7 shows that the fixed track was chosen in only six out of the 60 cases considered. The average burn and flight time differences between the fixed track (number 6) and the actual best fuel route was 7.2 minutes and 1230 kg for eastbound flights and 4.5 minutes and 877 kg for

*MFT_A refers to a minimum fuel track based on a verifying analysis.

**MFT_F refers to a minimum fuel track based on an operational forecast.

AMSTERDAM-CARACAS ROUTE SELECTION

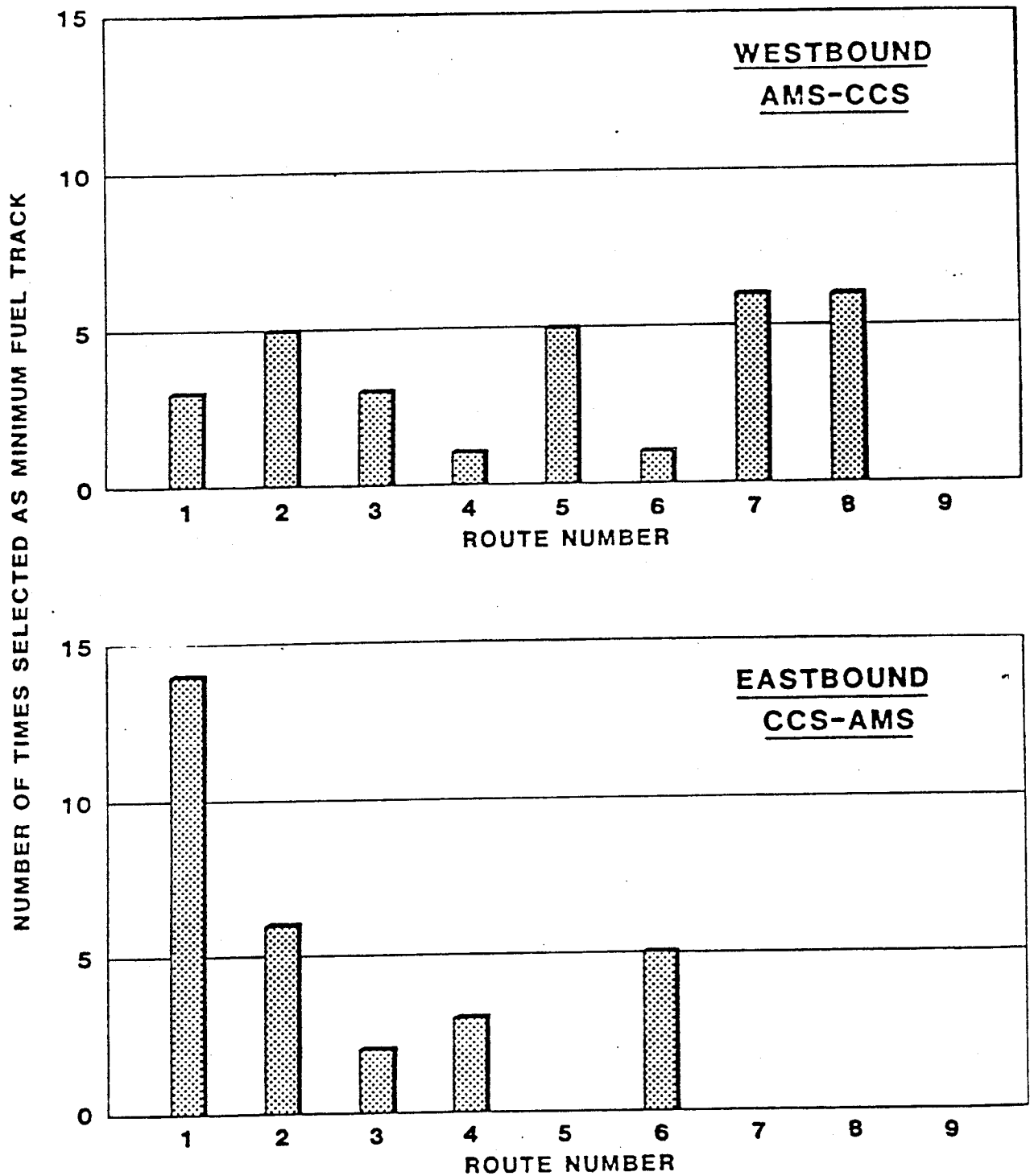


Figure 7. Shows the number of times the fixed track (#6) was optimal between Amsterdam-Caracas as compared to 8 other tracks set adjacent and separated by 120 nautical miles. These results were developed using a verifying analysis.

westbound flights. These results were developed using the verifying analysis.

2.3 Use of an Operational Forecast for Flight Planning

As part of the NASA study, the National Weather Service made available a 12, 18, 24 and 30 hour operational forecast, a 12, 18, 24 hour verifying analysis and numerous other data for a period of 33 days which were chosen in a Monday-Friday sequence between August and November 1979 (2 days in January 1979 were also included). Only the verifying analysis was changed by the addition of observations from AIDS* equipped aircraft. Typically between 200 and 400 additional observations were provided by AIDS on the North Atlantic during a given 24 hour period. The results showed that the impact on the analysis of a 50 to 100 percent increase in pilot reports was minimal.⁶ In general, then the verifying analysis was impacted only slightly (except in data void areas) and the intended objective of an improved verifying analysis for comparison purposes was not achieved.

In order to obtain a more complete understanding of the impact of the operational forecast on flight

*AIDS systems provided automatically position and wind velocity from aircraft inertial system and temperature, altitude and time from other on-board systems at 200 km intervals.

planning a series of additional comparisons were made. Winds and temperatures from operational flight plans were compared with the data from the actual flights. Over three thousand flight segments were compared.⁷ The results showed that the average algebraic difference between the forecast and observed wind speed was minus 9 knots without considering direction, and the average difference in the component of the forecast wind parallel to the direction of the observed wind was minus 13 knots; both indicating that the Suitland forecast on average underestimates the wind speed. The root mean square (RMS) vector error was 30.1 knots. These results are presented in several forms so that they may be meaningful to the widest audience. It was believed that traditionally pilots and others concerned with flight planning refer to wind "forecast error" as the difference between the two scalar quantities wind direction and wind speed. Using this definition of "forecast error" the mean forecast error for all segments was found to be 13.8 kts., 28.5 degrees for wind and 2.9°C for temperature. These results, according to the above definition, are shown in Figures 8 (for the Blue Airlines) and Figure 9 (for the Red Airlines) as the algebraic differences as well as the absolute value of the difference between the forecast and observed values; additional data on parallel, and cross components, and the root mean square (RMS) vector

Figure 8. Average Segment Differences Between Flight Plan Forecast and Actual Observations for Blue Airline

	<u>NORTH ATLANTIC</u>		<u>POLAR</u>		<u>MID ATLANTIC</u>		<u>ALL</u>
	<u>Eastbound</u>	<u>Westbound</u>	<u>Eastbound</u>	<u>Westbound</u>	<u>Eastbound</u>	<u>Westbound</u>	
<u>ALGEBRAIC DIFFERENCES</u>							
Wind Direction (degrees)	-5.4	-4.2	+69.0	-17.9	-13.0	0.9	-4.5
Wind Speed (knots)	-8.3	-9.0	-18.0	-11.4	-14.4	-5.0	-8.7
Temperature (°C)	-2.3	-2.5	-1.0	-1.7	+0.4	-1.0	-2.4
<u>ABSOLUTE VALUE OF DIFFERENCES</u>							
Wind Direction (degrees)	22.0	29.8	109.0	43.3	57.9	56.8	28.5
Wind Speed (knots)	15.3	13.0	19.5	16.3	14.4	9.4	13.8
Temperature (°C)	3.0	3.0	1.5	2.2	2.7	1.5	2.9
<u>DIFFERENCE IN PARALLEL COMPONENT (knots)</u>							
	-13.6	-17.0	-34.3	-19.8	-17.8	-10.5	-16
<u>DIFFERENCE IN CROSS COMPONENT (knots)</u>							
	-4.4	-3.0	-5.0	-8.7	-2.8	0	-3.5
<u>MAGNITUDE OF VECTOR DIFFERENCE (knots)</u>							
	26.2	24.9	35.5	26.5	22	18.5	25.2
<u>RMS OF VECTOR ERROR</u>							
	33.7	33.6	38.3	31.0	23.3	20.3	33

Source: PRC Analysis of BLUE Airline Data

Figure 9. Average Segment Differences Between Flight Plan Forecast and Actual Observations for Red Airline

	<u>NORTH ATLANTIC</u>		<u>POLAR</u>		<u>ALL</u>
	<u>Eastbound</u>	<u>Westbound</u>	<u>Eastbound</u>	<u>Westbound</u>	
<u>ALGEBRAIC DIFFERENCES</u>					
Wind Direction (degrees)	+1.9	-2.0	-3.8	-2.6	-1.0
Wind Speed (knots)	-6.4	-4.2	-5.7	-9.2	-5.3
Temperature (°C)	+2.0	+1.7	-0.7	+0.4	+1.5
<u>ABSOLUTE VALUE OF DIFFERENCES</u>					
Wind Direction (degrees)	13.5	21.7	22.3	24.8	19.6
Wind Speed (knots)	15.3	11.5	12.4	14.0	12.9
Temperature (°C)	3.1	3.0	2.8	2.7	3.0
<u>DIFFERENCE IN PARALLEL COMPONENT (knots)</u>					
	-9.2	-7.6	-8.7	-12.0	-8.0
<u>DIFFERENCE IN CROSS COMPONENT (knots)</u>					
	+3.4	-3.1	+0.6	-2.0	-0.9
<u>MAGNITUDE OF VECTOR DIFFERENCE (knots)</u>					
	24.0	18.7	18.1	19.0	20.2
<u>RMS OF VECTOR ERROR</u>					
	28.5	21.9	23.8	22.3	24.0

Source: PRC Analysis of RED Airline Data

error is also provided. These results tend to indicate that the accuracy of the verifying analysis as well as the operational forecast were limiting factors in the flight plan comparisons developed by the contractor. In order to more completely document the impact of the operational forecast on flight planning for the 33 days (Monday-Friday schedule between August and November) of rerun data available, flight segments with differences between forecast (flight plan) and observed (AIDS system on aircraft) data which exceeded any one or more of the following criteria:

1. wind speed greater than 20 knots
2. wind angle greater than 30 degrees
3. temperature greater than 5°C

were identified. A detailed analysis (independent of the flight plan) of those days which met or exceeded any of the above criteria showed that 15 of the 33 days were found to have significant forecast errors.⁸ These forecast errors were basically of two types: (1) underestimation of wind speed, and (2) repetition of forecast errors.

2.3.1 Underestimation of Wind Speed

A persistent error found throughout the analysis was the underestimation of winds. In 14 of the forecast error situations, the forecast maximum winds were at least 20 to 25 knots and sometimes more than 50 knots

under forecast. Wind speeds further away from the core were proportionately in error out to the 50 knot level where the errors become insignificant.

2.3.2 Repetition of Forecast Errors

In the analysis it was noted that apparent forecast errors were not corrected on subsequent forecasts. Review of the forecasts issued 12 or 24 hours later showed that errors were propagated from forecast to forecast even though the intervening analysis showed many actual observations that were in disagreement with the forecast. A forecast, for example, that showed a maximum wind isotach of 90 knots would be followed by another with a 90 knot maximum isotach even though winds of 125 to 135 knots were observed at the valid time of the forecast. Sometimes, the same situation would have occurred 24 hours earlier and 24 hours later as well, with the forecasts providing no indication of stronger winds. This repetition of the forecast errors was confirmed on five of the 33 days reviewed.

2.3.3 Location of Synoptic Features

Location, movement, development and intensity of synoptic scale features were usually quite accurate. Only on five of the 33 days were the forecasts judged to have significant errors in this regard. Typically, these consisted of underestimating the extent of the

deepening of a trough which resulted in an extensive area of wind direction errors.

2.4 Airline Use of Weather Data for Flight Planning

Two different airline flight planning models were used in this study one identified as Blue and the other Red. The operational forecast used for flight planning in both cases was the Suitland seven level primitive equation forecast model. While the flight plan comparisons for each carrier are in agreement that the wind speeds are on average underforecast, there were some differences. Although each carrier agreed that the average segment temperature was in error by 3°C, one airline consistently found the forecast temperature too warm while the other found it too cold. In order to examine the differences between the two flight plan models used in this study, the criteria established in Section 2.3, namely;

1. wind speed greater than 20 knots
2. wind angle greater than 30 degrees
3. temperature greater than 5°C

were tabulated as a function of airline, to compare the flight plan generated forecast with observation (AIDS data). The comparisons showed that there were 2,349 segments for which any one or more of these limits were exceeded. Even though both flight plans used the same operational forecast, covered similar routes, and the Red airlines operated substantially fewer flights, the

Red airlines had a substantially higher number of error segments. The Blue airline had 528 error segments over 651 flights (0.8 per flight) while the Red airline had 858 error segments over 262 flights (3.2 per flight). Since both airlines used the same weather data, and the routes were similar, it is apparent that their utilization of the data (i.e., interpolation algorithms) could be different. Further investigation showed that the Red airline winds were often in disagreement with both the forecast and the verifying analysis.

2.4.1 Time Interpolation and Choice of Forecast

Results indicated that time interpolation between weather forecasts, or choice of forecast caused some of the wind differences between the forecast and the analysis, especially in rapidly changing situations.

2.4.2 Average Wind in Areas of Sharp Gradients

Where flight segments traverse areas of sharp wind speed and direction gradients, the interpolation algorithm used by the airline becomes very important. Many forecast error segments were found near the centers of highs, lows, ridges or troughs where the wind velocity is changing rapidly with distance.

III. Discussion of Results/Implications/Recommendations

3.1 North Atlantic Flight Operations

The results show that if the present operational forecast could be made available more often (closer to operational requirements for flight planning) so as to make the available data more current, then the average benefit in fuel savings which could be achieved is approximately 2.5 percent eastbound and 1.2 percent westbound (ATC has not been considered). If the detail inherent in the observations can be retained so that the forecast reflects both improvements in timeliness and accuracy then the average increase in fuel savings could rise by an additional 2.0 percent (average east-westbound value) over the above savings (based on the 75 MTT cases studied).

The results of the NAT track MTT/MFT comparisons raises important questions about the validity of the models and the techniques (i.e., fixed prog versus moving prog) used by all participants in the comparison (ATC and the Red and Blue Airlines) since the same operational forecast product was used in each case. Although in most cases there was only one track difference, the tracks were typically separated by 120 nautical miles, half the width of the jet stream. These results should be considered very conservative since if a manually developed analysis were used instead of the computer developed analysis the differences may have

been substantially greater, as has been demonstrated in the Gander comparisons.

Additionally, it has been shown that the flight plan models themselves may be introducing additional errors and distorting the forecast product.

The forecast model itself has also been shown to have limitations in underestimation of wind speed and repetition of forecast errors. The results of the 33 day study (over a 4-month period) shows that 15 of the 33 days had significant forecast errors. These are the type of errors which are small on the synoptic scale but are of major importance to fuel savings and improved aircraft operating efficiency. Beyond showing the magnitude of the wind errors it was not possible to quantify this potential through the flight plan because of forecast, verifying analysis and MTT model data input limitations. These results were developed using the 7 level primitive equation forecast model which was replaced in August 1980 by the Spectral model. The Flattery analysis is still being used operationally for the aviation digital forecast (ADF).

North Atlantic flight operations represent a system problem and a component of that system is weather. Wind and temperature data are used by Gander and Prestwick ATC centers to set the North Atlantic tracks and it is used by airlines to determine a preferred route prior to the track placement and to select a track and altitude

once the tracks have been set. It is important to note that both east and westbound tracks are set on a forecast based on an observation made 24 hours earlier. Most carriers fly the North Atlantic on an 18 to 24 hour forecast. The purpose of a moveable track system (as opposed to a fixed system) is to maximize the opportunity for safe, efficient and economical operation. Implicit in this concept has to be the idea that the tracks must be set on the most current and accurate information. The problem simply summed up is one of information management and the ability of the provider to get the most current and accurate data to the user in a timely manner; and the user (airlines, ATC centers) to process the data and provide a data output for efficient flight operations.

3.1.1 The Current ATC Time Lines (Eastbound) NAT

- A. Observations are collected around 000Z and 1200Z ± 3 hours.
- B. Aviation Digital Forecast for 12Z, 18Z, 24 and 30Z becomes available between 5 1/2 to 6 1/2 hours after observation time.
- C. Transmission to users requires an additional 2 to 3 hours.
- D. Gander gets the forecast at 0730Z - 0930Z; a computer develops a number of MTT's and a planner manually develops the eastbound

tracks, which are usually posted before 1400Z.

- E. Airlines in many cases cannot wait for the new forecast based on the 1200Z observation which becomes available between 1900Z and 2000Z, and so they flight plan on a forecast based on the 0000Z observation.

3.1.2 Recommendations

Using current technology it should be possible to save 12 hours in the airline/ATC process. One possible way of achieving this is the following:

- A. Provide a 12 hour forecast* (based on a 1200Z \pm 1 hour observation) transmitted and available for immediate use at 1500Z by an ATC center.
- B. Present computer technology can provide a computer developed minimum fuel track between 8 city pairs in 8 minutes.
- C. Track analysis/negotiation to set tracks can be completed in 60 minutes or less.
- D. At 1630Z airlines should be receiving the track message in preparation for flight planning (based on a forecast developed from the 1200Z observation).

*MERIT program concept of interactive forecast.

The above scenario requires (1) the availability of a forecast to meet user needs and (2) the processing and transmission of data at rates commensurate with present technology.

3.2 Mid Atlantic Flight Operations

Many of the recommendations for the North Atlantic can be applied to the Mid Atlantic Routes. These can be summarized as (1) an accurate forecast available at optimal times; (2) an accurate and fast minimum fuel track model and; (3) transmission of data commensurate with current technology. These recommendations are supported by the results shown in Figure 7 which indicate that the location of the fixed tracks between Caracas-Amsterdam were not optimal in most cases (54 out of 60 cases). These results should be considered to be conservative since the flight plans were generated using a computer developed rather than a manual verifying analysis.

3.3 Domestic/International Flight Operations

Most of the NASA study was concerned with international routes, although a number of flights were over the continental United States. The following conclusions should have equal validity in both the domestic and international environments:

1. The National Weather Services aviation digital forecast (ADF) provides reasonably accurate

weather information on the large-scale features of the atmosphere. These forecasts are hemispherical (soon to be almost global) in coverage and are on the synoptic (500-5000 km) scale. Advances in numerical prediction models are taking place and the spatial resolution has been improved (i.e., spectral model), however, we are still relying on a forecast model which is on the synoptic scale with its inherent spatial and temporal limitations. This means that large-scale features such as ridges and troughs are usually well defined. However, other characteristics such as precise location and intensity of jet streams, frontal systems and regions of sharp gradients which are critical input for accurate flight planning cannot be seen with sufficient resolution. Clearly, broad scale synoptic developments exercise a controlling influence on the weather and are extremely important, but within this framework there are subsynoptic scale features that will inevitably be lost or smoothed out when using a forecast which has an effective spatial resolution of 1000 km (600 miles) or more (at 60° north).

2. In a high fuel cost environment the aviation community requires a special forecast product

which is designed specifically for its needs. The product should meet the following conditions:

- a. sufficient resolution to provide details of atmospheric features necessary for accurate flight planning.
- b. availability and frequency to coincide with individual airline flight planning schedules and operational requirements.
- c. demonstrated cost effective potential.

Given the present and near term economic climate it seems appropriate to limit recommendations to what is possible with existing data sources and currently available technology.

The problem facing the aviation community in terms providing a tailored weather product is basically not one of technology but one of data processing, management and dissemination. This is the type of problem which can be adequately addressed with existing technology.

3.3.1' Data Sources

The aviation digital forecast, pilot reports (pireps), rawinsonde and satellite data make up the present upper air aviation data base. The limitations of the aviation digital forecast have already been discussed, but there is no question that it is needed and it will play a key role in any future aviation digital data base. The pirep has the potential of

providing a major data source for accurate flight planning. It has been undervalued in the past because it was considered unreliable and prone to a high error rate. The tendency of the model developers not to trust the pirep (for good reasons) has resulted in a low weighting of the pirep and is at least partly responsible for the high level of data smoothing which has been a major limiting factor in the development of an accurate flight plan. The pirep has come of age. It contains the weather information which the aviation industry must have, and it can make a major contribution to improved aircraft operating efficiency. The technology is now available (i.e., ACARS-down link) to have an automated pirep system. The demonstrated quality control possibilities, and low error rates of the automated pireps can be an important ingredient in an accurate flight planning system for the 1980's.

Satellite data has an important role to play in providing an accurate data base. The present visible and infra-red images can be used to provide verification of the aviation digital forecast. It may prove especially valuable when used to provide advance warning on the stability and movement of particular weather systems. This type of information may also be of value in identifying periods where significant weather related errors in flight planning are possible.

Additionally, infra-red satellite pictures from VAS (VISSR Atmospheric Sounder) has the potential to provide quantitative information on subsynoptic scale features important to aviation. VAS is expected to become operational in 1985-1986 time period.

The present rawinsonde-twice per day observing system is expected to remain in place for the next 5 to 10 years before anticipated changes begin to occur.

3.3.2 Data Processing/Data Management

Data processing/data management refers specifically to the ability to ingest and process the aviation digital forecast, pireps, rawinsonde and satellite data hereafter referred to as "aviation weather data". The "aviation weather data sets" are complementary in nature see Figure 10. Each has limitations and advantages. These sets need to be combined so that the advantages are optimized for maximum useful information output. The basic technology to accomplish this has been developed and hardware is available, however, the software is not. The purpose of the NASA MERIT (Minimum Energy Routes Using Interactive Techniques) program is to validate and verify the techniques to fill this software gap.⁹

3.3.3 Data Dissemination - Domestic Carriers

What can be done to improve the dissemination of the ADF? A possible solution is priority transmissions

Figure 10. Complementary Nature of Data Base Available for Flight Planning

DATA SOURCE	ADVANTAGES	DISADVANTAGES	HORIZONTAL/VERTICAL RESOLUTION
NUMERICAL FORECAST MODEL	PROVIDES TIME - ENVOLVING 3D PICTURE OF ATMOSPHERE	INADEQUATE SPATIAL RESOLUTION	1000KM/100MB
AIRCRAFT REPORTS	DETAILED, TIMELY	HORI ZONTAL, VERTICAL COVERAGE LIMITED	500KM/ 1KM (ON NORTH ATLANTIC)
SATELLITES	TIMELY DETAILED DATA ON SHAPE OF JET	DOES NOT PROVIDE DIRECT OBSERVATION - NEEDS SUBJECTIVE INTERPRETATION	500KM/4KM

of bulletin #21 for domestic airlines. The present scenario is the following: The operational ADF is transmitted to the carriers at a rate of 1050 bits/sec. (negotiations are in progress to increase this to 4800 bits/sec.). The 12 hour forecast is first transmitted and this is followed by the 18, 24 and 30 hour forecast. Each forecast is now hemispherical in coverage and provides data for a number of different levels in the atmosphere. The transmission time for each forecast period is between 35 and 45 minutes (including error related re-transmissions). Each hemispherical forecast period is also divided into a number of bulletin areas (i.e., North America #21, North Atlantic #22, etc.). There are approximately 16 bulletin areas. A domestic carrier, has a requirement for the 12, 18, 24 and 30 hour forecast for bulletin area #21, and gets the 12 hour forecast within 40 to 45 minutes, but it will take another 80 to 90 minutes to get the 18 and 24 hour forecast, or a total transmission time of 160 minutes if the 30 hour forecast is also received. The basic problem is most of the data is not required for domestic operations.

One approach to improve the transmission problem for the domestic air carriers is to have a dedicated transmission/circuit which provides to them at 4800 bits/sec. only bulletin area #21 for the 12, 18, 24 and 30 hour forecast. This means that all domestic carriers

would have ingested the 12 and 18 hour forecast in under 5 minutes after transmission has begun. In a similar manner, a separate 9600 bits/sec. circuit could provide international carriers with appropriately optimized bulletin areas and forecasts to meet their operational requirements.

The above suggestion is based on the assumption that a National Weather Service generates all the forecast fields prior to the beginning of its sequential transmission, and that parallel simultaneous transmissions can be made depending upon user requirements. There is, however, a fundamental parameter which has a direct bearing on transmission rates, and that is forecast model resolution.

3.3.4 Forecast Model Resolution/Data Transmission Rates

As improved forecast models and observations become available, there will be a need to transmit more data, not less. The aviation industries' requirements are to be provided with weather data which can accurately define those meteorological occurrences which have a direct and immediate impact on flight safety, and economical and efficient operations. As higher resolution data become available along airline routes the data density will increase and so will the transmission rates just to keep the total transmission

time constant. An important question is, what model resolution is necessary to meet airline requirements as stated above and what would be the required data transmission rate? An answer to this question would provide guidance as to where the aviation industry is headed on these matters.

3.3.5 Forecast Models - Domestic Carriers

A potential benefit can be obtained domestically if the Limited Area Fine Mesh Model (LFM) output could be made available on an operational basis. It is understood that the LFM could be available operationally 2 to 2 1/2 hours earlier than the current operational ADF. Besides having a higher resolution, its earlier availability may offer improved domestic flight planning. Initial evaluation of the LFM as an adjunct to the ADF is very encouraging.^{10,11}

3.3.6 Forecast Models - International Carriers

It was intended to repeat 14 days of flight plan comparisons using the Bracknell forecast model, however technical considerations and cost presented this from occurring. With the cooperation of the Civil Aviation Authority* (CAA) a number of cases have been rerun

*Mr. Joseph Irving of the CAA has provided all the comparison data. His efforts on behalf of the NASA study have been substantial. It is anticipated that a report discussing the results in depth may be available within 12 months.

comparing flight plans developed on a Bracknell forecast with those developed on a Bracknell verifying analysis. These cases (done manually) did not involve the calculation of MTT's but looked at specific routes actually flown by aircraft. Preliminary results show a small improvement and are very similar to those developed by PRC Speas with the Suitland forecast.

International air carriers will shortly be making major decisions concerning the forecast model itself and the transmission of the data. The choice of forecast model (Suitland or Brocknell) as well as the data transmission mode/rate are interdependent and should not be treated separately. These decisions will set the standard for the next one or perhaps two decades and should be carefully considered. The choices are not easy nor simple because they require a knowledge of present and future system improvements.

There are a number of points which need to be made:

Suitland

1. The current aviation digital forecast product uses a Flattery model (which is scheduled to be changed to the multivariate type by the end of the year) to analyze the observations and the Spectral forecast model to move it forward in time (12, 18, 24 and 30 hours). The data is outputted on a $2\frac{1}{2}^{\circ} \times 5^{\circ}$ grid (north of 20° north) and this means that the spatial resolution of the output grid is

significantly finer than the spatial resolution of both the analysis and forecast models.

2. Suitland will be getting a new and faster computer within the next 12 months which should be operational by 1984, with a new multivariate analysis and the Spectral forecast model.
3. Suitland presently transmits a full forecast at 1050 bits/seconds. It takes 2 1/2 to 3 1/2 hours for most carriers to receive this data. Suitland has proposed to change the transmission rate to 4800 bits/sec.

Bracknell

1. Bracknell is currently providing a 10 level forecast model for all latitudes north of 20° north and is outputted on a 2 1/2° x 5° grid. In all probability this grid resolution is finer than the model resolution.
2. Bracknell has obtained a new computer which is 30 times faster than the one it replaces. A new 15-level model has been developed which has a spatial resolution of 1 7/8° x 1 1/2° and will be outputted on a 2 1/2° x 5° grid. In this case the model resolution will be finer than the gridded output. The new forecast model is expected to be operational within several months.

3. Bracknell presently transmits the 10 level forecast data in the Suitland format at 9600 bits/sec.

Recently there has been an interest in transmitting the middle data set (at $2\ 1/2^\circ$) in order to provide more accurate weather information for flight planning. As can be seen from the above data the accuracy of the present Suitland and Bracknell aviation data base cannot be improved by this approach. Likewise, interpolation to the $2\ 1/2^\circ$ point (by whatever method) would be counterproductive. The new Bracknell forecast model may offer additional opportunities in this area since the forecast model resolution is higher than that of the gridded output. However, an evaluation of the Bracknell model would be required before it can be recommended.

IV. Summary/Conclusion

The objective of the NASA study was to determine if more timely and accurate weather data could provide (via the flight plan) improved operating efficiency and fuel savings for carriers. The complicating factors such as ATC and the age of the weather data were eliminated in an attempt to simplify the study. The verifying analysis was used as "actual weather" but it was clear that it was limiting the accuracy of the results, and was circumvented by comparing flight plan developed with observed winds and temperatures (after

appropriate averaging). Finally, the airline flight plan (i.e., interpolation algorithms) as a potential source of error, was removed by a direct comparison of the observed winds with weather service operational charts in order to determine if it was a forecast or a flight plan error. All these comparisons and much more have been made and evaluated. The results show that a conservative estimate for potential fuel savings on long distance flights (over 2000 km) would be between 2 and 4 percent depending upon the direction of flight (beneficial impact on reserve fuel has not been considered). These savings would only be possible if:

1. A way was found to make more timely and accurate data available for flight planning and flight following.
2. An ATC system was in place which would support MFT routing.
3. Some form of enroute automated pirep system (i.e., ACARS) was operational.

There is good reason to believe that if the above system changes were made that the potential for fuel savings would be even higher than shown in this study. This speculative assumption is based on the following:

1. Much of the study utilized data from August through November which does not represent the most dynamic and rapidly changing weather situations

which occur normally during November through April.

2. All of the "high resolution data" which was used in the study had a spatial resolution of 175 km (110 miles) and was limited in area of coverage in both the horizontal and the vertical. As such one did not get a look at the fine structure of the atmosphere. It is knowledge of this fine structure which can provide the most efficient minimum fuel track routing.

The potential sources of error limiting improved aircraft operating efficiency from a weather point of view have been shown to be the following:

1. the accuracy of the forecast product;
2. the accuracy of the flight plan model;
3. the accuracy of the MFT/MTT models used by carriers and ATC.

A common theme which has persisted throughout this study has been the need to revise and update concepts and approaches which are based on 1960's technology. The aviation weather data base needs to be brought in line with current airframe and engine technology.

The airline flight plan has virtually remained unchanged since 1965 when it was automated. It needs to be updated to reflect the quality of the forecast input and advances in computer technology. For example:

1. The MFT/MTT flight planning model represents old technology;
2. The space and time interpolation model used should reflect the forecast model spatial resolution;
3. The information content and presentation should be tailored for the user.

An airline, whether it has developed its own flight plan in the past or purchases a service should critically review the technical details of the model in order to determine its real cost to their operation.

The air carriers should become familiar with the potential as well as the limitations of the operational forecast products which are available. For example, the ADF output grid resolution (as inputted to the flight plan) is not necessarily the same thing as the forecast model resolution. The difference can be very costly in terms of carrier operating efficiency regardless of the route length.

The air carriers are aware of the fact that the aviation digital forecast is one of many products provided by a national weather service, but it is not really a special product designed to meet airline needs. However, it does provide a reasonably good hemispheric forecast on the synoptic scale (500-5000 km).

World-wide the airlines used between 30 and 35 billion gallons of fuel last year. Two percent is

almost 700 million dollars. For a small capital investment of (about one percent of the potential savings) between 7 to 9 million dollars and an annual operating budget of 1 to 2 million dollars the airlines collectively could have the most advanced operational aviation forecast center in existence providing a first-class tailored aviation product for most air carriers (note: it would still be dependent on a National Weather Service Forecast as part of the input data set). This approach is not new. This is the concept that spawned Aeronautical Radio Incorporated (ARINC) in 1936. The forcing function then (and now) was a common interest, and a need and a desire to avoid duplication and waste. However, because of a number of economic and other factors, it will probably not happen.

It is clear that the National Weather Services provide an important product, one the aviation industry cannot do without. However, at cruise altitudes a higher spatial resolution is needed in both the horizontal and the vertical than can presently be provided, even by an advanced hemispherical forecast model. The forecast product needs to be tailored in both time and space to meet the aviation needs in a high fuel cost environment.

Efficient and cost-effective operation dictates that the tailoring of the weather product be developed

at a single location (i.e., a national weather service); however, realistically it may not happen this way.

Most probably several strong carriers will become interested in this concept (perhaps when they consider updating their flight planning procedures) and will move into this area. There will be a number of smaller carriers who will also recognize the advantage of a tailored forecast, and their needs will eventually be met by the private sector, probably as part of a complete flight planning service.

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